Residue Management and Herbicides for Downy Brome (*Bromus tectorum*) Control in Kentucky Bluegrass Grown for Seed

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Recent changes in herbicide registrations and governmental restrictions on field burning raised many management questions for Kentucky bluegrass seed producers, particularly the extent to which useful lives of their stands might be shortened by decreasing crop yields or increasing weed pressure. Tests conducted over the lives of two grass seed stands (1993–1997) evaluated three contrasting methods of postharvest residue management (vacuum sweep, bale/flail chop/rake, and field burn) and 13 herbicide treatments. Downy brome was the primary weed at both the Madras and LaGrande, OR, sites. In nontreated checks and the four least effective herbicide treatments, downy brome populations increased exponentially over time, with year-to-year increases in density averaging 13.1-fold. Competition had easily detected effects on Kentucky bluegrass seed yield at densities of 30 downy brome plants/m^2, and crop stands were destroyed beyond 100 to 200 weeds/m^2. Both PRE terbacil at 840 g/ha and early POST (EPOST)/late POST (LPOST) split-applied primisulfuron at 20 g/ha per application contained downy brome during the first 2 yr but not the third, when crop injury from terbacil forced reduction in terbacil rate and changes in weed populations overcame primisulfuron. PRE terbacil followed by LPOST primisulfuron, EPOST terbacil plus primisulfuron followed by LPOST primisulfuron, and EPOST/LPOST split-applied terbacil plus primisulfuron achieved excellent control of downy brome until the final years of the study, when control became increasingly erratic as primisulfuron-resistant downy brome proliferated in specific individual plots. Injury from combination terbacil plus primisulfuron treatments reduced yield relative to safest treatments in early years when downy brome population densities were low.

Nomenclature: Dicamba; metribuzin; oxyfluorfen; primisulfuron; terbacil; downy brome, *Bromus tectorum* L. BROTE; Kentucky bluegrass, *Poa pratensis* L. POAPR.

Key words: Postharvest residue management, nonburned grass seed production.

Weeds affect grass seed production by competing with crops and contaminating harvested seed (Lee 1966; Mueller-Warrant 1990; Mueller-Warrant and Rosato 2002). Historically, Pacific Northwest Kentucky bluegrass seed producers have controlled seedling grasses by late summer postharvest field burns followed by early to mid-fall PRE or early POST (EPOST) applications of terbacil, diuron, or metribuzin; and late fall late POST (LPOST) applications of diuron, metribuzin, oxyfluorfen, or high rates of dicamba (Lee 1965; Mueller-Warrant and Neidlinger 1994). These and other herbicides were registered for use in grass seed crops on the basis of field trials demonstrating their ability to control weeds with acceptable levels of crop injury. Unlike turf, where any visual damage may be objectionable, moderate to occasionally severe visual injury can be tolerated in grass seed production as long as the crop recovers in time to yield well the following harvest. The ability of grass seed growers to burn their fields was drastically reduced by legislation adopted in Oregon in 1991 and by more recent judicial and executive decisions in Washington. Early studies evaluating mechanical alternatives to open field burning for postharvest residue removal identified the importance of weed control in the success or failure of nonburned grass seed production (Chilcote et al. 1980; Lee 1974; Young et al. 1984). Political

pressures to limit field burning have raised questions of what effects alternative methods of residue management might have on Kentucky bluegrass seed production and on weeds such as downy brome. Downy brome is often the primary weed forcing Kentucky bluegrass stands out of production, doing so both by direct competition and by adding to the fuel load, thereby causing very hot fires that "burn out" patches of the crop and increase space available for further weed invasion. During preliminary tests of the ability of primisulfuron to selectively control quackgrass [*Elytrigia repens* (L.) Nevski] in Kentucky bluegrass grown for seed, potential to control downy brome was also discovered (C. Buchholz, personal communication, 1992).

Although both crop injury and weed control efficacy can be simultaneously measured in herbicide field trials, researchers often conduct studies emphasizing precision in measuring one of those aspects at the expense of the other. Crop tolerance studies are usually conducted on highly uniform crop stands, and weeds of interest may be entirely absent or present at too low a density for accurate evaluation of their control. Weed control efficacy studies are usually conducted in areas with moderate to high density of weeds arising either from deliberate introduction of seed or other propagules by the researcher or naturalized occurrence of large weed patches. Crop stands may be quite variable, especially in naturalized weed patches where previous competition has weakened perennial crops or where multifactor interactions have impeded establishment of annual crops. Because of uncertainties Kentucky bluegrass seed growers faced regarding future changes in herbicide registrations, field burning regulations, and downy brome biology, we were concerned

not only with how well herbicides would control this weed and how safe they would be on the crop, but also with how downy brome populations would evolve over time and how much damage to the crop would be caused by various densities of this weed. The specific objective of this research was to observe the effects of the best available herbicide treatments on downy brome control and Kentucky bluegrass seed production under three alternative methods of post-harvest residue management over the entire life of two stands, one in central Oregon at Madras and one in eastern Oregon at LaGrande.

Materials and Methods

General Procedures and Residue Management Treatments. Tests were conducted in irrigated grass seed fields of 'Abbey' (Central Oregon Agricultural Research Center, Madras, OR) and 'Baron' (LaGrande, OR) Kentucky bluegrass. Both stands were planted in 1992, received no grass control treatments while establishing, and produced their first seed crops in July 1993. Cooperators used standard practices for fertilization (200 kg/ha N split-applied in fall, early spring, and mid-spring) and disease control (three applications of 0.12 kg/ha propiconazole[1] applied from early May through late June). Residue management treatments were imposed after each harvest from 1993 through 1996 to the same main plots, which were 18.3 by 41.1 m at Madras and 14.0 by 41.1 m at LaGrande. Residue management treatments included traditional field burn, thorough residue removal (vacuum sweep), and bale/flail chop/rake. Bale/flail chop/rake plots were baled, flail chopped to a 4-cm stubble height, and then raked to uniformly distribute remaining residue using a 'Needle-Nose' rake.[2] In vacuum sweep plots, after straw was baled the remaining stubble was cut to a 2-cm height with a flail head and blown into an enclosed wagon for removal. In field burn plots, straw was spread uniformly across plots and burned. Residue management treatments were arranged as main plots in a randomized complete block design with four replicates per site, and herbicide treatments were randomized as subplots within each of the main plots, creating a traditional split-plot arrangement of the two treatment factors.

Herbicide Treatments. A total of 15 herbicide treatments, including the nontreated check, were applied as subplots 2.7 m wide by 18.3 m long at Madras and 14.0 m long at LaGrande within residue management main plots, but data are only being reported for 13 treatments kept consistent over time. Herbicides were applied at 243 L/ha under 207 kPa pressure using a commercial test plot sprayer pulled by a four-wheel all-terrain-vehicle at 4.2 km/h. The spraying system included bypass agitation that was adjusted by an MT-3000 Sprayer Monitor[3] to maintain constant delivery rate. Herbicide treatments were applied to the same plot locations each year to follow the buildup of downy brome populations over time. Terbacil rate was reduced by 20% in the 1995–1996 growing season to a yearly total of 672 g/ha because of carryover in the soil and crop damage the previous growing season in plots that had received 840 g/ha per year terbacil in single or split applications (Table 1). All primisulfuron-containing treatments included 0.25% v/v nonionic surfactant.[4]

Herbicide treatments were altered for the 1996–1997 growing season to evaluate the impact of downy brome competition on Kentucky bluegrass seed yield, to measure the performance of terbacil plus primisulfuron treatments at differing densities of downy brome, and to search for primisulfuron-resistant plants. In each main plot that year, three subplots were nontreated while 12 others received EPOST terbacil at 336 g/ha plus primisulfuron at 20 g/ha followed by either LPOST terbacil at 336 g/ha plus primisulfuron at 20 g/ha (for the more vigorous plots) or LPOST primisulfuron at 20 g/ha alone (for plots with thinner stands due to terbacil carryover and injury). Highlights of data from this final growing season are summarized in the text but not presented in tabular or figure format.

Weed Density, Crop Injury, and Seed Yield Measurement Procedures. Downy brome plants were counted in central 30.1 m^2 areas of each plot the first and second years at LaGrande and the first, third, and fourth years at Madras; in central 24.2 m^2 areas the second year at Madras; and in central 26.0 m^2 areas the third and fourth years at LaGrande. Plots in which downy brome density appeared likely to exceed 50 plants/m^2 were subsampled using a movable grid identifying 1,100 locations per plot to examine for the presence/absence of central crowns of individual downy brome plants. Subsampled data were then adjusted to an equivalent whole plot count basis using values obtained with both methods in 10 weedy plots at Madras in 1995 through 1997 and LaGrande in 1997. Crop injury was visually rated relative to a hypothetical full stand with no stunting or discoloration, and nontreated checks were only considered to have 0% injury if none of the crop stand within them had been lost to competition from downy brome.

Plots were trimmed before harvest to 16.8 m long at Madras and 12.2 m at LaGrande. Swath width was 1.5 m, taken from the center of the 2.7-m-wide plots. Plots were swathed into windrows between midnight and 10:00 A.M. to minimize seed shatter, combined with a small plot combine when dry, and stored in polypropylene bags until seed cleaning. Windrows were covered with bird netting to minimize disturbance by wind between swathing and combining. Postharvest residue in each main plot was raked into windrows, baled, and weighed to determine straw yield on a main-plot basis. Straw was returned after weighing to field burn plots. Harvest index was determined by dividing the clean seed yield by the sum of the precleaned seed yield and the straw yield. Seed samples were rethreshed on a stationary thresher just before final cleaning. Air-screen cleaners were adjusted to produce separate, nearly pure samples of Kentucky bluegrass and downy brome seed for each plot. Data for straw yield, harvest index, and downy brome seed yield are not being reported in the interest of manuscript length.

Statistical Analyses. Treatments at each site were arranged in a simple split-plot factorial design, with three residue management main plots randomized within each of four replications, while 13 herbicide treatment subplots were

Table 1. Dates of management operations by harvest year. Kentucky bluegrass yearly cropping cycle is viewed as beginning with postharvest residue management operations, followed by PRE, early POST (EPOST), and late POST (LPOST) herbicide applications, BROTE density measurement, crop injury rating, and ending with swathing and combining.

	Madras				LaGrande			
Operation	1993–1994	1994–1995	1995–1996	1996–1997	1993–1994	1994–1995	1995–1996	1996–1997
	Date of management practice (and BROTE growth stage at herbicide application)							
Baling	August 16	July 22	August 7	August 15	August 11–12	August 4–5	August 2–3	August 7–8
Needle-nose raking	August 16	July 22	August 25	August 15	August 11–12	August 4–5	August 2–3	August 7–8
Flail chopping	August 16	July 22	August 22	August 15	August 11–12	August 4–5	August 2–3	August 7–8
Vacuum sweeping	August 16	July 22	August 29	August 15	August 11–12	August 4–5	August 2–3	August 7–8
Field burning	August 5		September 6	August 19	August 11–12	August 4–5	August 2–3	August 9
PRE herbicide	September 29 (3–4 LF)	September 13 (true PRE)	September 19 (1 LF)	—	September 23 (true PRE)	September 14 (1 LF)	September 19 (4 LF)	—
EPOST herbicide	October 27[a] (2–3 tiller)	October 27 (2–3 LF)	October 13 (3 LF)	September 30 (1 LF)	October 28 (1 tiller)	October 5 (2–3 LF)	September 19 (4 LF)	October 3 (2 LF)
LPOST herbicide	October 27 (2–3 tiller)	December 21 (5–10 tiller)	December 18 (3–12 tiller)	November 25 (1–2 tiller)	October 28[b] (1 tiller)	November 16 (2–4 LF)	November 28 (3–10 tiller)	November 14 (1 tiller)
BROTE density	April 26	April 13	April 8	April 25	April 28	April 11	April 10	May 1
Crop injury	April 27	April 13	April 8	April 30	April 28	April 12	April 10	May 1
Swathing	July 2	July 6	July 9	July 2	July 17	July 14	July 16	July 11
Combining	July 19–20	July 27–28	July 23–24	July 18–19	August 2–3	August 1–2	August 5–7	August 1–2

[a] EPOST timing for primisulfuron 20 EPOST/primisulfuron 20 LPOST, terbacil 840 + primisulfuron 20 EPOST/primisulfuron 20 LPOST, and terbacil 420 + primisulfuron 20 EPOST/primisulfuron 20 LPOST in the 1993–1994 growing season at Madras was September 29, 1993.

[b] LPOST timing for primisulfuron 20 EPOST/primisulfuron 20 LPOST, terbacil 840 + primisulfuron 20 EPOST/primisulfuron 20 LPOST, and terbacil 420 + primisulfuron 20 EPOST/primisulfuron 20 LPOST in the 1993–1994 growing season at LaGrande was March 8, 1994.

randomized within each of the individual main plots. Because the full set of treatments was applied at each of two locations and was reapplied in each of three consecutive growing seasons, it was also possible to conduct analyses viewing the six site-years as main plots, the three residue management treatments as subplots, and the 13 herbicide treatments as subsubplots. Data for each site-year separately and all six site-years pooled together were subjected to goodness-of-fit chi-square tests of normality using a nominal set of 14 bins potentially providing chi-squares with 11 degrees of freedom (Steel et al. 1997).

Bartlett's chi-square test for homogeneity of variances was conducted on all analyses of data pooled over site-years (Steel et al. 1997). Where transformed data were normal but heterogeneity of variances still existed among site-years, data were analyzed separately for each site-year. Where heterogeneity of variances among site-years was not found at the $P = 0.001$ level of significance, analysis pooled over site-years was presented.

Results and Discussion

Downy Brome. Examination of the Madras test site before its initial harvest in July 1993 revealed widely scattered downy brome at a density of approximately 0.1 plants/m^2. No attempt was made to rogue these plants, and their seed would have been widely scattered during combining and postharvest residue management operations in 1993. Density of downy brome at the LaGrande test site before the initial harvest in July 1993 was even lower than at Madras. Analysis of the impact of residue management and herbicide treatments on downy brome density was complicated by the wide range in densities encountered throughout the course of the study. Nonzero downy brome density differed by nearly four orders of magnitude between the cleanest plots in 1994 and the weediest ones in 1996. Additionally, 17% of plots at Madras and 44% of plots at LaGrande had absolutely no downy brome present in the spring of 1994, with several individual plots remaining weed-free through the spring of 1996.

F-tests from ANOVA of logistically transformed downy brome density indicated the presence of significant site-year effects, residue management effects, herbicide treatment effects, herbicide treatment by site-year interactions, and herbicide treatment by residue management interactions (Table 2). Site-year main effects and herbicide treatment by site-year interactions are presented in Table 3, whereas residue management main effects, herbicide treatment main effects, and herbicide treatment by residue management interactions are presented in Table 4.

Downy brome density in the nontreated check and the four most poorly performing herbicide treatments increased exponentially from year to year, with an average yearly increase of 13.1-fold (Table 3). When averaged over all treatments, the mean yearly increase in downy brome density was 9.1-fold. When averaged over the three best treatments, the mean yearly increase was 4.8-fold. The least effective treatment was LPOST dicamba, which differed from the nontreated check only the first 2 yr at Madras (Table 3) and when applied in conjunction with field burning averaged over site-years (Table 4). Tank-mixing oxyfluorfen with dicamba

Table 2. Probability values for goodness-of-fit chi-square normality tests, Bartlett's homogeneity of variances tests, and analysis of variance F-tests.

Statistical test and site-year	Raw BROTE/m²	Log(1+BROTE/m²)	Logistic BROTE[a]	Arcsine square root percent crop injury[a]	Seed yield (kg/ha)	Seed yield (% of site-year avg.)
Goodness-of-fit normality tests	————————————————	Observed P values for rejection of null hypothesis	————————————————			
Normality: Madras 1994	<0.0001	0.0122	0.0152	0.0122	0.8567	0.8567
Normality: Madras 1995	<0.0001	0.0461	0.0421	0.1471	0.0747	0.0747
Normality: Madras 1996	<0.0001	0.0005	0.2889	0.0238	0.2584	0.2584
Normality: LaGrande 1994	<0.0001	<0.0001	0.1156	0.0080	0.1401	0.1401
Normality: LaGrande 1995	<0.0001	<0.0001	0.1210	0.1352	0.9196	0.9196
Normality: LaGrande 1996	<0.0001	0.0213	0.1412	0.0430	<0.0001	<0.0001
Normality: all site-years pooled	<0.0001	<0.0001	0.0152	0.0743	<0.0001	0.0033
Homogeneity of variances tests						
Bartlett's test: all site-years pooled	< 0.0001	<0.0001	0.0042	<0.0001	<0.0001	<0.0001
Bartlett's: omit LaGrande 1996	—	—	—	—	<0.0001	<0.0001
ANOVA: all site-years pooled						
F-test: site-year (SY)	<0.0001	<0.0001	<0.0001	0.0004	<0.0001	—
F-test: residue management (RM)	<0.0001	<0.0001	<0.0001	0.2688	0.8036	0.7057
F-test: RM × SY	<0.0001	0.0244	0.1211	0.2938	0.0183	0.0888
F-test: Herbicides (H)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
F-test: H × SY	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
F-test: H × RM	<0.0001	<0.0001	0.0031	0.0131	0.0793	0.0815
F-test: H × RM × SY	0.0006	0.4022	0.4124	0.0154	0.4888	0.2739
ANOVA: Madras 1994						
RM	0.3797	0.2708	0.2653	0.2570	0.0992	0.0992
H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
H × RM	0.4233	0.4481	0.4695	0.0102	0.0611	0.0611
ANOVA: Madras 1995						
RM	0.0467	0.0178	0.0090	0.7481	0.2008	0.2008
H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
H × RM	0.0694	0.3116	0.0699	0.0799	0.6604	0.6604
ANOVA: Madras 1996						
RM	0.0093	0.0337	0.0360	0.0065	0.1059	0.1059
H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
H × RM	0.0106	0.7574	0.6556	0.1291	0.5519	0.5519
ANOVA: LaGrande 1994						
RM	0.7772	0.5814	0.1861	0.4007	0.0767	0.0767
H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
H × RM	0.7211	0.6330	0.3650	0.1492	0.0014	0.0014
ANOVA: LaGrande 1995						
RM	0.4631	0.3487	0.1384	0.5349	0.5914	0.5914
H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
H × RM	0.0139	0.0178	0.1171	0.5977	0.3062	0.3062
ANOVA: LaGrande 1996						
RM	0.0469	0.0423	0.0223	0.3704	0.4451	0.4451
H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
H × RM	0.0010	0.0044	0.1849	0.1989	0.3478	0.3478

[a] ANOVA F-test probability values for logistic BROTE and arcsine square-root percent crop injury are from F-test averages of 33 Monte Carlo simulations replacing all observed 0 values with random small numbers ranging from 0.003 to 0.027 BROTE/m² and −0.55 to 0.35% crop injury. Normality tests are the median values of 101 Monte Carlo simulations for logistic BROTE and arcsine square-root percent crop injury. Bartlett's homogeneity of variances tests are the median values of 33 Monte Carlo simulations for logistic BROTE and arcsine square-root percent crop injury.

improved control over dicamba alone the third year at Madras (Table 3) and with both vacuum sweep and bale/flail chop/rake residue management, but not field burning (Table 4). The next two least effective treatments overall were LPOST oxyfluorfen plus metribuzin and LPOST primisulfuron. The oxyfluorfen plus metribuzin treatment reduced downy brome density compared to the nontreated check in all cases except the second and third years at Madras (Tables 3 and 4). LPOST primisulfuron reduced downy brome density compared to the nontreated check in all cases, but generally not as

well as treatments containing terbacil or split EPOST/LPOST applications of primisulfuron or terbacil plus primisulfuron. EPOST application of 560 g/ha terbacil plus 840 g/ha oxyfluorfen was more effective than LPOST primisulfuron the third year at both Madras and LaGrande (Table 3) and with both vacuum sweep and bale/flail chop/rake residue management, but not field burning (Table 4). EPOST/LPOST split-applied primisulfuron was more effective than EPOST terbacil plus oxyfluorfen the second and third years at Madras (Table 3) and when applied in conjunction with field

Table 3. Site-year by herbicide treatment interaction on downy brome density, averaged over postharvest residue management treatments.

Herbicide treatment (g ai/ha)	Downy brome (BROTE) density in early spring of each harvest year[a]					
	Madras			LaGrande		
	1994	1995	1996	1994	1995	1996
	Plants per m^2					
Untreated check	6.53 e	34.91 i	95.27 gh	0.31 g	3.03 g	37.92 f
Primisulfuron 20 early POST (EPOST)/primisulfuron 20 late POST (LPOST)	0.98 cd	1.21 d	2.87 cd	0.07 ef	0.10 cd	4.81 cd
Terbacil 840[b] PRE	0.07 b	0.42 c	16.26 e	0.04 cde	0.08 bc	2.47 bc
Terbacil 840[b] + primisulfuron 20 EPOST/primisulfuron 20 LPOST	0.05 ab	0.25 bc	0.70 ab	0.02 abc	0.02 a	0.21 a
Dicamba 2240 LPOST	0.77 cd	10.45 gh	139.63 h	0.35 g	2.55 g	53.49 f
Terbacil 840[b] PRE/dicamba 2240 LPOST	0.02 a	0.10 ab	6.50 de	0.02 abcd	0.13 cde	3.65 bc
Oxyfluorfen 280 + dicamba 2240 LPOST	0.47 cd	8.22 fgh	77.96 fg	0.16 fg	1.87 g	32.25 f
Terbacil 560 + oxyfluorfen 840 EPOST	0.44 c	3.82 ef	13.84 e	0.06 def	0.23 def	2.09 bc
Primisulfuron 39 LPOST	0.97 cd	5.49 fg	41.47 f	0.04 cde	0.38 f	12.79 e
Terbacil 420[b] + primisulfuron 20 EPOST/terbacil 420[b] + primisulfuron 20 LPOST	0.05 ab	0.24 bc	1.65 bc	0.01 a	0.03 a	0.40 a
Terbacil 840[b] + primisulfuron 39 LPOST	0.49 cd	1.58 de	4.09 cd	0.02 ab	0.03 ab	1.81 b
Terbacil 840[b] PRE/primisulfuron 39 LPOST	0.83 cd	0.08 a	0.37 a	0.02 abc	0.06 abc	0.24 a
Oxyfluorfen 280 + metribuzin 420 LPOST	1.16 d	15.63 hi	60.47 fg	0.04 bcde	0.29 ef	11.74 de
Site-year means	0.37 Y	1.61 X	12.23 W	0.05 Z	0.19 Y	3.95 X

[a] Data were analyzed using a logistic transformation, log([number BROTE per m^2/223]/[1 − number BROTE per m^2/223]), to normalize variances, conduct analysis of variance, and perform means separation tests. Data were transformed back to raw density per m^2 for tabular presentation. Values followed by the same lowercase letter within a column do not differ at the P=0.05 level of significance. Values followed by the same uppercase letter within a row do not differ at the P=0.05 level of significance.

[b] Terbacil rate reduced by 20% in the 1995–1996 growing season to a yearly total of 672 g/ha due to carryover in soil and crop damage the previous growing season.

burning (Table 4). PRE terbacil was more effective than EPOST/LPOST split-applied primisulfuron the first two years at Madras, but was less effective the third year, when terbacil rates were reduced by 20% in treatments that had received 840 g/ha per year for the two previous years because of crop injury from accumulating terbacil (Table 3). PRE terbacil was more effective than EPOST/LPOST split-applied primisulfuron in vacuum sweep and bale/flail chop/rake residue management, but not field burning (Table 4). LPOST terbacil plus primisulfuron was more effective than PRE terbacil the third year at Madras and the first year at LaGrande, but was less effective the first two years at Madras (Table 3). Application of LPOST dicamba following PRE terbacil improved control of downy brome over terbacil alone only the first 2 yr at Madras (Table 3) and when applied in conjunction with field burning (Table 4).

The three most effective treatments were EPOST terbacil plus primisulfuron followed by LPOST primisulfuron, EPOST terbacil plus primisulfuron followed by LPOST terbacil plus primisulfuron, and PRE terbacil followed by LPOST primisulfuron. PRE terbacil followed by LPOST primisulfuron was less effective than the other two treatments

Table 4. Residue management by herbicide treatment interaction on downy brome density, averaged over site-years.

Herbicide treatment (g ai/ha)	Downy brome (BROTE) density in early spring of each harvest year[a]			
	Postharvest residue management treatment			
	Vacuum sweep	Bale/flail chop/rake	Field burn	Herbicide means
	Plants per m^2			
Untreated check	8.08 g Z	14.70 fg Z	10.31 j Z	10.71 g
Primisulfuron 20 early POST (EPOST)/primisulfuron 20 late POST (LPOST)	0.36 de Z	1.59 d Y	0.62 de Z	0.70 d
Terbacil 840[b] PRE	0.14 bc Z	0.64 bc Y	0.72 def Y	0.40 c
Terbacil 840[b] + primisulfuron 20 EPOST/primisulfuron 20 LPOST	0.06 a Z	0.14 a Y	0.12 a YZ	0.10 a
Dicamba 2240 LPOST	4.89 g Z	17.53 g Y	4.64 i Z	7.41 g
Terbacil 840[b] PRE/dicamba 2240 LPOST	0.12 bc Z	0.39 b Y	0.27 c YZ	0.24 b
Oxyfluorfen 280 + dicamba 2240 LPOST	1.99 f Z	8.45 f Y	4.10 hi YZ	4.12 f
Terbacil 560 + oxyfluorfen 840 EPOST	0.57 e Z	1.14 cd YZ	1.33 fg Y	0.95 d
Primisulfuron 39 LPOST	2.00 f YZ	3.28 e Y	1.17 ef Z	1.98 e
Terbacil 420[b] + primisulfuron 20 EPOST/terbacil 420[b] + primisulfuron 20 LPOST	0.08 ab Z	0.18 a Y	0.12 ab YZ	0.12 a
Terbacil 840[b] + primisulfuron 39 LPOST	0.20 cd Z	0.72 bc Y	0.39 cd YZ	0.38 c
Terbacil 840[b] PRE/primisulfuron 39 LPOST	0.08 ab Z	0.14 a YZ	0.25 bc Y	0.14 a
Oxyfluorfen 280 + metribuzin 420 LPOST	1.43 f Z	4.04 e Y	2.55 gh YZ	2.45 e
Postharvest residue management means	0.47 N	1.32 L	0.86 M	0.81

[a] Data were analyzed using a logistic transformation, log([number BROTE per m^2/223]/[1 − number BROTE per m^2/223]), to normalize variances, conduct analysis of variance, and perform means separation tests. Data were transformed back to raw density per m^2 for tabular presentation. Values followed by the same lowercase letter within a column do not differ at the P=0.05 level of significance. Values followed by the same uppercase letter within a row do not differ at the P=0.05 level of significance.

[b] Terbacil rate was reduced by 20% in the 1995–1996 growing season to a yearly total of 672 g/ha due to carryover in soil and crop damage the previous growing season.

the first year at Madras, more effective than the other two treatments the second year at Madras, and more effective than EPOST terbacil plus primisulfuron followed by LPOST terbacil plus primisulfuron the third year at Madras (Table 3). These three treatments were equally effective all 3 yr at LaGrande. EPOST terbacil plus primisulfuron followed by LPOST primisulfuron was more effective than PRE terbacil followed by LPOST primisulfuron when applied in conjunction with field burning (Table 4).

In general, bale/flail chop/rake residue management had the highest downy brome density, vacuum sweep had the lowest, and field burn had intermediate density, with field burn averaging 82% more downy brome than vacuum sweep and bale/flail chop/rake averaging 54% more than field burn (Table 4). However, there were herbicide treatments in which residue management patterns differed somewhat from these general ones. There were no detectable differences among residue management treatments for the nontreated check. Field burn and vacuum sweep did not differ from each other for 9 of 12 herbicide treatments, bale/flail chop/rake and field burn did not differ for 9 of 12 herbicide treatments, and vacuum sweep and field burn did not differ for 4 of 12 herbicide treatments.

In 1996 we began to seriously consider the possibility that three consecutive years of treatment had selected for increased resistance to primisulfuron in the downy brome populations at both Madras and LaGrande. The primary initial evidence that this might have occurred was the increasingly erratic performance of what had been our three most successful treatments, EPOST terbacil plus primisulfuron followed by LPOST primisulfuron, EPOST terbacil plus primisulfuron followed by LPOST terbacil plus primisulfuron, and PRE terbacil followed by LPOST primisulfuron. We developed a model of plot-to-plot redistribution of downy brome seed from swathing, combining, and postharvest residue management operations to better differentiate plots in which downy brome densities were stable or declining over time from those experiencing exponential increases in this weed. Most plots receiving the three most highly effective treatments had ratios of downy brome density in one year to density the previous year in areas contributing seed of less than one. However, a number of individual plots receiving these three treatments were identified in which downy brome exhibited exponential year-to-year increases in density. At Madras, six plots showed such behavior from both 1994 to 1995 and 1995 to 1996, and two more plots only from 1995 to 1996. At LaGrande, nine plots showed such behavior from both 1994 to 1995 and 1995 to 1996.

The modified set of herbicide treatments applied in the 1996–1997 growing season confirmed our suspicions that downy brome populations at both sites were indeed increasing in resistance to our best treatments, tank mixes and sequential applications of terbacil and primisulfuron. The average increase in downy brome density in plots that were nontreated in the 1996–1997 growing season was 33.2-fold at Madras and 48.3-fold at LaGrande. In plots treated in the 1996–1997 growing season with EPOST terbacil plus primisulfuron followed by LPOST primisulfuron, downy brome density increased by more than 2.5-fold in 38% of cases at Madras

and 32% of cases at LaGrande. In plots treated with EPOST terbacil plus primisulfuron followed by LPOST terbacil plus primisulfuron, downy brome density increased by more than twofold in 17% of cases at Madras and 2% of cases at LaGrande. Archived downy brome seed samples from all four harvests at both sites were subsequently tested for resistance to primisulfuron, and a detailed analysis of the evolution of resistance will be published as a separate manuscript.

Laboratory studies to determine the physiological basis for acetolactase synthase (EC 4.1.3.18) (ALS) inhibitor resistance in the Madras biotype and in another biotype collected in a Kentucky bluegrass seed grower's field in Athena, OR were conducted subsequent to the field studies described in the current manuscript (Mallory-Smith et al. 1999; Park and Mallory-Smith, 2004; Park et al. 2001; Park et al. 2002; Park et al. 2004). While the Athena biotype displayed a classic single-base-pair point mutation in the ALS gene conferring a high level of resistance, ALS extracted from the Madras biotype was susceptible to inhibition. The Madras biotype possessed a moderate level of whole-plant resistance to a wide variety of ALS-inhibiting herbicides, resistance that could be overcome by application of organophosphate insecticides, suggesting enhanced ability to metabolize herbicides as the primary mechanism of resistance. This biotype was also found to possess the classic chlorophyll $psbA_{264}$ point mutation resistance to photosystem II inhibitors such as atrazine and metribuzin (K. W. Park, personal communication, 2005). Poorer performance of oxyfluorfen plus metribuzin at Madras than at LaGrande may have been a consequence of photosystem II inhibitor resistance in the Madras population, but frequency of occurrence of photosystem II inhibitor resistance was not directly measured.

The Central Oregon Agricultural Research Center at Madras is located on the boundary between irrigated agriculture in the Agency Plains Irrigation District and noncrop areas of the Madras Industrial Park. While no detailed records exist for past herbicide use on the specific field in which our test was conducted or in adjacent areas, it is highly likely that ancestors of our herbicide-resistant downy brome were treated with a wide variety of herbicides, including multiple applications of atrazine, chlorsulfuron, and sulfometuron. Our three best combination terbacil plus primisulfuron treatments achieved an average of 95% control of downy brome, potentially increasing the frequency of resistance by 20-fold each year, or 8,000-fold over a 3-yr period (Gressel and Segel 1982). This level of selection pressure was clearly adequate to unmask resistance that had been hidden within these downy brome populations. It was, however, much smaller than the selection pressure classically considered necessary to fix mutations occurring at a background frequency of 10^{-6} to 10^{-7} as dominant genotypes within a population. The additional selection pressure was almost certainly provided before the initiation of our experiments.

Crop Injury. While arcsine square-root percent transformation of crop injury was able to normalize the data at each site-year, combined analysis over time could not be conducted because of heterogeneity of variances (Table 2). Residue management by herbicide treatment interaction occurred in only one case, the first year at Madras, at an observed

Table 5. Residue management and herbicide treatment main effects on Kentucky bluegrass crop injury, by site-year.

| | Visual rating of crop injury in early spring[a] | | | | | |
| | Madras | | | LaGrande | | |
Main effect means	1994	1995	1996	1994	1995	1996
Postharvest residue management main plot treatments	—————————————————— % crop injury ——————————————————					
Vacuum sweep	1 a	17 a	5 a	9 a	3 a	6 a
Bale/flail chop/rake	1 a	14 a	7 a	8 a	4 a	5 a
Field burn	0 a	20 a	13 b	11 a	3 a	6 a
Herbicide subplot treatments (g/ha)						
Untreated check	0 a	4 a	0 a	0 a	0 a	0 a
Primisulfuron 20 early POST (EPOST)/primisulfuron 20 late POST (LPOST)	0 a	4 a	2 ab	4 b	1 bc	2 b
Terbacil 840[b] PRE	2 b	34 cd	20 e	10 cd	10 g	17 d
Terbacil 840[b] + primisulfuron 20 EPOST/primisulfuron 20 LPOST	6 c	16 b	15 de	26 e	12 g	20 d
Dicamba 2240 LPOST	0 a	13 ab	3 abc	0 a	0 ab	0 a
Terbacil 840[b] PRE/dicamba 2240 LPOST	2 b	47 de	21 e	12 d	9 fg	15 d
Oxyfluorfen 280 + dicamba 2240 LPOST	0 a	11 ab	2 ab	0 a	0 ab	0 a
Terbacil 560 + oxyfluorfen 840 EPOST	0 a	12 ab	5 bc	6 b	3 de	9 c
Primisulfuron 39 LPOST	0 a	13 ab	2 ab	7 bc	1 bc	0 a
Terbacil 420[b] + primisulfuron 20 EPOST/terbacil 420[b] + primisulfuron 20 LPOST	2 b	18 bc	9 cd	30 e	9 fg	16 d
Terbacil 840[b] + primisulfuron 39 LPOST	1 b	10 ab	3 abc	30 e	5 ef	6 c
Terbacil 840[b] PRE/primisulfuron 39 LPOST	0 a	55 e	33 f	30 e	8 fg	21 d
Oxyfluorfen 280 + metribuzin 420 LPOST	0 a	9 ab	13 de	13 d	2 cd	4 bc
Interaction F-test significance (P level)	0.010	0.080	0.129	0.149	0.598	0.199

[a] Data were analyzed using the arcsine square-root percent transformation to normalize variances, conduct analysis of variance, and perform means separation tests. Data were transformed back to raw percentage crop injury for tabular presentation. Values followed by the same lowercase letter within a treatment factor (postharvest residue management main plots or herbicide treatment subplots) within a column do not differ at the P=0.05 level of significance.

[b] Terbacil rate reduced by 20% in the 1995–1996 growing season to a yearly total of 672 g/ha due to carryover in soil and crop damage the previous growing season.

P=0.0102. However, average crop injury in this case was so low that the interaction has little practical significance.

The most severely injured treatment the first year at Madras, EPOST terbacil plus primisulfuron followed by primisulfuron, had only 6% damage (Table 5). By the second year, all three treatments at Madras that received the full rate of terbacil at PRE timing were severely injured, with 55% damage for PRE terbacil followed by LPOST primisulfuron. Compared to PRE timing, delaying application of terbacil until EPOST greatly reduced crop injury the second and third years at Madras. Reducing maximum terbacil rates the third year at Madras had the intended effect of reducing crop injury. One of the extra treatments not included in ANOVA of crop injury (Tables 2 and 5) was 840 g/ha terbacil applied to weedy plots that had not previously been treated with terbacil. This treatment caused 60% injury, indicating that even a single year's use of the full terbacil rate could seriously damage Kentucky bluegrass that had been weakened by competition with downy brome. Primisulfuron caused relatively minor injury at Madras in any year.

Somewhat different patterns of injury occurred at LaGrande, with PRE terbacil causing less damage and EPOST terbacil plus primisulfuron causing more damage than at Madras. Primisulfuron caused more injury at LaGrande than it had at Madras, perhaps due to higher soil pH or differential cultivar sensitivity. Greatest injury at LaGrande occurred in the first year, unlike Madras. Despite the 20% reduction in maximum terbacil rates the third year at LaGrande, injury increased for many treatments compared to the second year. Injury symptoms for terbacil and primisulfuron differed, with terbacil causing severe bleaching and death of leaf tissue while primisulfuron caused slight yellowing of leaves and general stunting of growth.

The extent of differences in cultivar sensitivity to primisulfuron was explored in research initiated before the conclusion of the experiments described in the current manuscript (Mueller-Warrant 1998). Of 12 Kentucky bluegrass varieties tested for tolerance to primisulfuron during their establishment year, Abbey and Baron, the varieties grown at Madras and LaGrande, were found to be less sensitive than nine other varieties. In light of these findings, language was added to registrations being written for use of primisulfuron on Kentucky bluegrass urging caution on the part of growers when treating varieties that they had not previously tested for tolerance to primisulfuron, especially in conditions of low downy brome population density.

Kentucky Bluegrass Seed Yield. Nontransformed seed yield data were normally distributed all 3 yr at Madras and the first 2 yr at LaGrande (Table 2). All attempts to normalize the LaGrande 1996 harvest data failed, and inspection of histograms revealed the presence of excessive numbers of very-low-yielding plots, with mean seed yield depressed below median seed yield and both mean and median seed yields depressed below mode seed yield for data grouped in arbitrary seed yield intervals of 20 to 40 kg/ha. Plots with abnormally low yields in 1996 tended to have extremely high densities of downy brome, with Kentucky bluegrass ground cover ratings in the spring of 1997 approaching zero.

Kentucky bluegrass seed yield represents integrated effects of competition with downy brome and crop injury from residue management and herbicide treatments. Because many of the treatments causing the most serious crop injury were also the ones providing the best downy brome control, it was logical to expect that seed yield performance of treatments would shift

Table 6. Postharvest residue management and herbicide treatment main effects on Kentucky bluegrass seed yield, by site-year.

| | Kentucky bluegrass clean seed yield [a] | | | | | |
| | Madras | | | LaGrande | | |
Main effect means	1994	1995	1996	1994	1995	1996
Postharvest residue management main plot treatments	—————————————————kg/ha—————————————————					
Vacuum sweep	705 b	896 a	438 a	338 ab	457 a	757 a
Bale/flail chop/rake	768 ab	875 a	327 b	356 a	493 a	724 a
Field burn	848 a	790 a	373 ab	321 b	514 a	766 a
LSD (among residue management treatments, P=0.05)	133	132	106	30	133	80
Herbicide subplot treatments (g/ha)						
Untreated check	789 cde	752 e	260 fgh	369 a	554 bc	633 cde
Primisulfuron 20 early POST (EPOST)/primisulfuron 20 late POST (LPOST)	853 abc	1122 a	536 ab	382 a	387 efg	838 a
Terbacil 840[b] PRE	663 fg	738 e	286 fgh	362 a	580 abc	812 a
Terbacil 840[b] + primisulfuron 20 EPOST/primisulfuron 20 LPOST	625 gh	991 a–d	449 b	313 bc	322 g	841 a
Dicamba 2240 LPOST	741 def	865 cde	257 fgh	371 a	498 cde	466 f
Terbacil 840[b] PRE/dicamba 2240 LPOST	559 h	530 f	310 efg	344 abc	538 bcd	801 ab
Oxyfluorfen 280 + dicamba 2240 LPOST	715 efg	825 de	297 fg	378 a	569 bc	603 def
Terbacil 560 + oxyfluorfen 840 EPOST	806 bcd	922 b–e	409 cd	354 ab	645 ab	814 a
Primisulfuron 39 LPOST	896 ab	989 a–d	403 cde	346 ab	353 fg	667 bcd
Terbacil 420[b] + primisulfuron 20 EPOST/terbacil 420[b] + primisulfuron 20 LPOST	782 cde	1030 abc	513 bc	248 e	438 def	785 ab
Terbacil 840[b] + primisulfuron 39 LPOST	929 a	1079 ab	611 a	302 cd	427 d–g	898 a
Terbacil 840[b] PRE/primisulfuron 39 LPOST	839 abc	474 f	347 def	268 de	348 fg	762 abc
Oxyfluorfen 280 + metribuzin 420 LPOST	857 abc	781 e	253 gh	365 a	685 a	814 a
LSD (among herbicide treatments, P=0.05)	90	177	93	43	112	140
Interaction F-test significance (P level)	0.061	0.660	0.552	0.014	0.306	0.348

[a] Values followed by the same lowercase letter within a treatment factor (postharvest residue management main plots or herbicide treatment subplots) within a column do not differ at the P=0.05 level of significance.

[b] Terbacil rate reduced by 20% in the 1995–1996 growing season to a yearly total of 672 g/ha due to carryover in soil and crop damage the previous growing season.

over time as downy brome density increased. At Madras in 1994, two herbicide treatments outyielded the nontreated check, LPOST primisulfuron and LPOST primisulfuron plus terbacil, while seven other herbicide treatments yielded on par with the check (Table 6). All three treatments yielding less than the check included a full rate of terbacil applied at either PRE or EPOST timing. There was a significant residue management effect, with field burn outyielding vacuum sweep by 143 kg/ha of clean seed. Yield with bale/flail chop/rake management was intermediate, and did not differ significantly from either vacuum sweep or field burn.

In the first year at LaGrande, none of the herbicide treatments outyielded the nontreated check, while eight of the treatments yielded on par with it. The four treatments yielding less than the check at LaGrande were the ones with highest ratings of crop injury (Table 5), and were also among those most effective in controlling downy brome (Table 3). There was a significant residue management effect, with bale/flail chop/rake outyielding field burn by 45 kg/ha of clean seed. Yield with vacuum sweep was intermediate, and did not differ significantly from either bale/flail chop/rake or field burn. The residue management by herbicide treatment interaction in 1994 at LaGrande consisted primarily of yields of all four most seriously injured herbicide treatments being reduced in field burn management, while only three of them were reduced in bale/flail chop/rake management, and only two in vacuum sweep.

In the second year at Madras, competition from downy brome reduced Kentucky bluegrass seed yield to such an extent that five herbicide treatments outyielded the nontreated check, five yielded on par with it, and only two yielded less

than it (Table 6). The five treatments outyielding the check were EPOST primisulfuron followed by LPOST primisulfuron, EPOST terbacil plus primisulfuron followed by LPOST primisulfuron, EPOST terbacil plus primisulfuron followed by LPOST terbacil plus primisulfuron, LPOST primisulfuron, and LPOST terbacil plus primisulfuron. Only one treatment yielded less than the check in both 1994 and 1995, PRE terbacil followed by LPOST dicamba. There was no residue management effect the second year at Madras.

The second year at LaGrande, one herbicide treatment outyielded the check, LPOST oxyfluorfen plus metribuzin (Table 6). Five treatments yielded on par with the check, and six treatments yielded less than it. The four treatments yielding less than the check in both 1994 and 1995 were EPOST terbacil plus primisulfuron followed by LPOST primisulfuron, EPOST terbacil plus primisulfuron followed by LPOST terbacil plus primisulfuron, LPOST terbacil plus primisulfuron, and PRE terbacil followed by LPOST primisulfuron. Because downy brome density the second year at LaGrande was similar to that the first year at Madras (Table 3), crop injury from herbicide treatments rather than competition with downy brome remained the primary reason for reductions in yield the second year at LaGrande, as it had been in the first. There was no residue management effect the second year at LaGrande.

The third year at Madras, six of the herbicide treatments outyielded the check, six of the treatments yielded on par with it, and none yielded less than it (Table 6). Two treatments outyielded the check in all 3 yr, LPOST primisulfuron and LPOST terbacil plus primisulfuron. Two other treatments yielded on par with the check the first year and outyielded it

the second and third years, EPOST primisulfuron followed by LPOST primisulfuron and EPOST terbacil plus primisulfuron followed by LPOST terbacil plus primisulfuron. There was a significant residue management effect, with vacuum sweep outyielding bale/flail chop/rake by 111 kg/ha of clean seed. Yield with field burn was intermediate, and did not differ significantly from either bale/flail chop/rake or vacuum sweep. Yield effects of residue management were likely caused by corresponding differences in downy brome density, as vacuum sweep had the fewest weeds and bale/flail chop/rake the most (Table 4), with Madras 1996 having the highest overall density of downy brome (Table 3).

The third year at LaGrande, eight of the herbicide treatments outyielded the check, three of the treatments yielded on par with it, and one treatment yielded less than it (Table 6). The only treatment yielding on par with the check the first year and outyielding it the second and third years was LPOST oxyfluorfen plus metribuzin. The three treatments yielding on par with the check the first and second years and outyielding it the third year were PRE terbacil, PRE terbacil followed by LPOST dicamba, and EPOST terbacil plus oxyfluorfen. All treatments that included both terbacil and primisulfuron yielded less than the check both the first and second years, while those with only primisulfuron yielded less than the check just in the second year. In the third year, however, three of the four treatments including both terbacil and primisulfuron outyielded the check, as did one of the two treatments with only primisulfuron. Downy brome densities the third year at LaGrande were similar to those the second year at Madras, and competition with downy brome clearly affected Kentucky bluegrass seed yield more than injury from herbicides. There was no residue management effect the third year at LaGrande.

The modified set of herbicide treatments applied in the 1996–1997 growing season provided further insights into the relation between competition with downy brome and injury from herbicides in determining Kentucky bluegrass seed yield. At Madras, the 22 weediest nontreated plots averaged only 55 kg/ha clean seed yield at an average density of 838 downy brome plants/m^2. The 14 least weedy nontreated plots averaged 217 kg/ha clean seed yield at an average density of 70 downy brome plants/m^2. The eight weediest plots treated with EPOST terbacil plus primisulfuron followed by either LPOST primisulfuron or LPOST terbacil plus primisulfuron averaged only 57 kg/ha clean seed yield at an average density of 779 downy brome plants/m^2. The 18 next weediest herbicide-treated plots averaged 183 kg/ha clean seed yield at an average density of 72 downy brome plants/m^2, implying a 16% yield loss due to herbicide injury at equal densities of downy brome. That the benefits of controlling downy brome outweighed the negative effects of herbicide injury can be seen in the 62 cleanest and 58 next cleanest herbicide-treated plots, which averaged 363 and 317 kg/ha clean seed yield at average densities of 4 and 23 downy brome plants/m^2.

At LaGrande, the 26 weediest nontreated plots averaged only 123 kg/ha clean seed yield at an average density of 393 downy brome plants/m^2. The nine least weedy untreated plots averaged 524 kg/ha clean seed yield at an average density of 21 downy brome plants/m^2. The 27 weediest herbicide-treated plots averaged 384 kg/ha clean seed yield at an average

density of 21 downy brome plants/m^2, implying a 27% yield loss due to herbicide injury at equal densities of downy brome. That the benefits of controlling downy brome outweighed the negative effects of herbicide injury even in the more primisulfuron-sensitive stand at LaGrande can be seen in the 118 cleanest herbicide-treated plots, which averaged 469 kg/ha clean seed yield at an average density of six downy brome plants/m^2.

Plots with the greatest increases in downy brome density from 1996 to 1997 tended to be the ones with the lowest yields at both Madras and LaGrande. Natural breaks in the downy brome density increase data occurred at around 200 plants per m^2 (range without data from 103 to 422) at Madras and 100 plants per m^2 (range without data from 34 to 132) at LaGrande. Kentucky bluegrass seed yields in plots with downy brome density increases above these cutoffs averaged 18 and 26% of yields in plots below these cutoffs at Madras and LaGrande, respectively. These critical values for downy brome density increase seem to represent the point at which Kentucky bluegrass stands died out during competition with this weed. Ratios of downy brome density in 1997 to density in 1996 from our plot-to-plot seed redistribution model indicated 41- and 45-fold increases in downy brome density in the plots dying out from competition at Madras and LaGrande, respectively. These ratios are over three times higher than the average year-to-year increases that occurred in nontreated checks and ineffective herbicide treatments during the first 3 yr of our study, and indicate that conditions for downy brome establishment had improved in the final year of our study relative to the vigorous Kentucky bluegrass stands initially present at both sites.

Implications for Management

Control of downy brome is a mandatory, although often difficult to achieve, component of successful systems for multiple-year Kentucky bluegrass seed production. Field burning or aggressive removal of postharvest residues with the vacuum sweep technique reduced downy brome density compared to bale/flail chop/rake, but differences among residue management treatments averaged less than threefold. Downy brome showed potential for greater than 10-fold year-to-year increases in density in nontreated checks and in poorly performing treatments. To avoid exponential increases in downy brome density over time, herbicide treatments must therefore achieve better than 90% control each year. Among herbicides available for use on Kentucky bluegrass before registration of primisulfuron, only PRE application of terbacil came close to providing this level of control. Unfortunately, this treatment caused considerable crop damage, especially when reapplied annually. Split EPOST/LPOST applications of primisulfuron controlled downy brome about as effectively as PRE terbacil, with less serious crop damage. Tank-mixes and sequential applications of terbacil plus primisulfuron appeared to offer Kentucky bluegrass seed producers several ways to achieve nearly total control of downy brome without unacceptable crop damage. Unfortunately, 3 yr of these treatments were sufficient to select for downy brome biotypes resistant to primisulfuron and to tank-mixes of terbacil plus

primisulfuron. Because this selection occurred in research settings in which high populations of downy brome were physically adjacent to plots with high selection pressure, it is possible that resistance might be somewhat slower to appear in large commercial production fields treated more uniformly. However, a downy brome biotype with target site resistance to primisulfuron was discovered in a commercial Kentucky bluegrass seed production field in Athena, OR, around the same time that resistance was first suspected in our tests (Mallory-Smith et al. 1999). Archived downy brome seed samples from 1994 through 1997 harvests at Madras and LaGrande have been tested in the greenhouse for primisulfuron resistance, and further analysis of plot-to-plot and year-to-year variations in frequency of resistance should help identify mechanisms governing the spread of resistance in these tests.

Differences in crop tolerance to herbicide treatments between our sites combined with differences in downy brome density and herbicide tolerance over time confound attempts to answer the general question of which of these treatments is best. Crop damage from herbicide treatments like ours is highly likely to reduce yield if downy brome densities the previous year are less than 0.3 plants/m^2. Competition from downy is highly likely to reduce yield more than damage from herbicides if downy brome densities the previous year are more than 1.0 plants/m^2. As a practical matter, Kentucky bluegrass seed producers should err on the side of caution regarding crop safety when selecting herbicide treatments for the next growing season if downy brome densities before harvest were less than one plant/m^2, and err on the side of weed control efficacy otherwise, especially if they want to keep their fields in production for more than just the year in question.

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Acknowledgment

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